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Eddy-Current Testing of Fatigue Degradation in Additionally Heat-Treated Gas Powder Laser Clad NiCrBSi Coating under Contact Fatigue Loading

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Abstract. The paper studies the applicability of eddy-current technique to testing fatigue degradation in Ni-18.2Cr-3.3B-4.2Si coating, produced by gas powder laser cladding and subjected to additional high-temperature annealing at 1025 °C, under contact loading. It is demonstrated that eddy-current testing of fatigue degradation in Ni-18.2Cr-3.3B-4.2Si coating under contact loading after high-temperature annealing has certain limitations caused by the high brittleness of this coating. In this case, it is possible to test only a sharp increase in the sizes of contact damages, which occurs at 8×10^5 cycles under these loading conditions and results from the formation of a great number of peripheral ring cracks in the fracture zone; the eddy-current readings α decrease due to the increasing electrical resistivity of the coating. Testing can be performed by eddy-current measurements at high excitation frequencies of an eddy-current transducer (f=72-120 kHz), when the effect of the ferromagnetic steel base on the eddy-current readings α is minimum.

INTRODUCTION

During laser cladding of nickel-chromium coatings, rapid cooling (up to 10^3-10^4 °C/s) of the clad metal through heat conduction [1] results in the formation of metastable structural states characterized by the presence of a supersaturated solid solution and fairly dispersed particles of strengthening phases [2]. This suggests the possibility of improving the quality of the coatings by additional heat treatment, this being supported by the data found in the literature [2, 3]. It was first shown in [3] that high-temperature stabilization annealing at a temperature of 1000 to 1050 °C sharply increases the hardness and tribological properties of the Ni-18.2Cr-3.3B-4.2Si coating to the levels corresponding to the characteristics of this coating after laser cladding, or even exceeds them. Simultaneously, the thus formed coating is heat-stable and, consequently, retains high values of hardness and abrasive wear resistance when heated up to the temperature of stabilization annealing.

However, additional heat treatment of the clad coating may also cause its embrittlement. For example, 1050 °C annealing of nickel-based alloy specimens prepared by direct laser deposition [4], as in [3], increased abrasive wear resistance of the clad specimens. Simultaneously, the strength characteristics of the heat-treated specimen decreased 5 times under conditions of static tension for three-point bending, its plasticity being 2.5 times as low as that of clad specimen. This was explained by the precipitation of hard carbides on the grain boundaries, which acted as stress concentrators [4]. Therefore, it is urgent to study contact fatigue and the possibility to test the fatigue degradation of coatings produced by a treatment combining laser cladding and post cladding heat treatment. This paper aims at studying the applicability of the eddy-current technique to testing the fatigue degradation of gas powder laser clad Ni-18.2Cr-3.3B-4.2Si coating, subjected to additional high-temperature annealing at 1025 °C, under contact loading.

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EXPERIMENTAL PROCEDURE

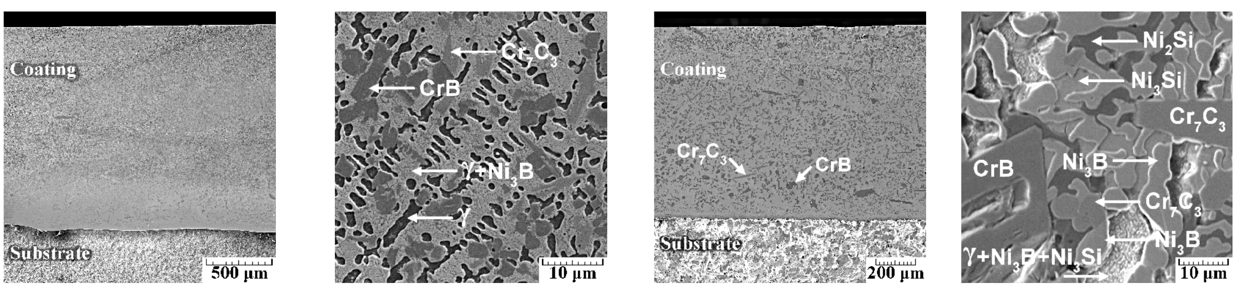
A powder blend of a self-fluxing NiCrBSi alloy (in wt%: 0.92 C, 18.2 Cr, 3.4 Fe, 4.2 Si, 3.3 B, and Ni for balance) with the particle size ranging between 40 and 160 μm served as the coating material. Low-carbon (0.20 wt% C) steel plate was clad with the powder blend by CO_2 continuous wave laser [5] using a radiation power of 1.4 to 1.6 kW, a speed of 160 to 200 mm/min, a powder consumption of 2.9 to 4.9 g/min, a surface laser spot size of 6×1.5 mm. The powder blend was transported to the cladding zone by an inert gas (argon) at 0.5 atm. To reduce surface stresses, the cladding was performed in two runs by overlaying one layer on another. The clad coating was subjected to mechanical grinding with high-intensity cooling to a coating thickness of 0.7 to 1.1 mm. After laser cladding, the coatings were heat-treated in a high-temperature vacuum electric furnace under the following conditions: heating to 1025 °C for 180 min, soaking at 1025 °C for 120 min, and cooling with the furnace [6].

Mechanical testing for contact fatigue was conducted on an Instron 8801 servohydraulic machine using a fixture of unique design [7] according to the pulsing non-impact “sphere-to-surface” contact scheme, with a periodically changing load, a steel ball diameter of 12.7 mm, the preloading P_0 = 0.1 kN, the maximum load P_{max} = 8.7 kN and the loading frequency f = 35 Hz based on N = 10^6 loading cycles. The coating structure and the phase composition were examined by a Tescan Vega II XMU scanning electron microscope (SEM) with X-ray wavelength-dispersive microanalysis and energy-dispersive microanalysis systems. X-ray diffraction analysis was made on a Shimadzu XRD-7000 diffractometer with CrK_α radiation. Microhardness was determined by the recovered indentation method on a Shimadzu HMV-G21DT microhardness tester at a load of 0.98 N, a loading rate of 40 μm/s, and load holding for 15 s. The electromagnetic parameters of the laser clad coating were measured on a laboratory EC instrument using a differentially connected attachable transformer transducer with a projecting ferrite pot core [8] at the frequencies f = 36, 72, 96, and 120 kHz.

RESULTS AND DISCUSSION

Two-layer laser cladding of the surface of a steel plate with NiCrBSi alloy powder results in a coating with an average microhardness of 970±40 HV0.1, whose metal matrix includes a Ni-based γ-solid solution and eutectics consisting of a γ-phase and Ni_3B boride, the strengthening phases being Cr_7C_3 carbide and CrB boride [9].

After additional heat treatment, the coating acquires a much coarser structure with large precipitations of the CrB and Cr_7C_3 strengthening phases (Fig. 1a) forming a high-strength wear-resistant framework [3], the sizes of these phases being comparable to those of the carbide particles of the composite coatings discussed in [10, 11]. According to the data of X-ray diffraction analysis and characteristic electron microprobe analysis (Fig. 1b), the Ni-18.2Cr-3.3B-4.2Si coating after high-temperature (1025 °C) annealing has the phase composition γ + Ni_3B + Cr_7C_3 + CrB + Ni_3Si + Ni_2Si. The microhardness of the coating after annealing increases to the value 1030±220 HV0.1.



(a) (b) (c) (d)

FIGURE 1. The general view (a, c) and microstructure (b, d) of the Ni-18.2Cr-3.3B-4.2Si coating after laser cladding (a, b) and additional heat treatment (c, d)

The results of contact fatigue tests for the Ni-18.2Cr-3.3B-4.2Si coating subjected to additional heat treatment are presented in Fig. 2. It is obvious from the data shown in Fig. 2a that the average contact spot diameter after 10^4 cycles of loading is 2.19 mm, which exceeds that of the as-clad Ni-18.2Cr-3.3B-4.2Si coating (1.88 mm), and it is on the level with the less heavily alloyed Ni-14.8Cr-2.1B-2.9Si coating (2.12 mm) [9]. As the number of contact loading cycles grows to $5×10^5$, the contact spot diameter increases continuously, and as the number of cycles grows from $8×10^5$ to 10^6, the size of contact damages increases sharply.

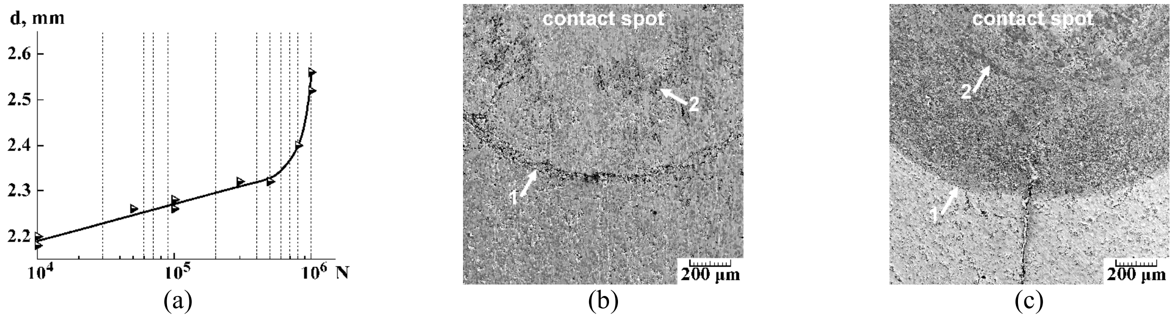


FIGURE 2. The influence of the number of loading cycles N on the contact spot diameter d (a) and SEM images of contact spots for the number of cycles N = 10^4 (b) and N = 10^6 (c) after contact fatigue testing of the Ni-18.2Cr-3.3B-4.2Si coating subjected to additional heat treatment

The electron microscopy examination of the contact spots (Fig. 2b, c) has shown that cracking and fretting develop in the process of contact fatigue loading of the tested coating. Surface cracking is characterized by the appearance of ring cracks (see Fig. 2b, c, shown by arrows 1) and radial cracks. The ring cracks appearing in the effective zone of maximum radial tensile stresses promote residual stress relaxation within the coating and cohesive failure (coating spalling at the contact spot edge) [10]. For the Ni-18.2Cr-3.3B-4.2Si coating subjected to additional heat treatment, ring cracking is observed as early as after 10^4 loading cycles (see Fig. 2b). After 5×10^5 cycles, the ring cracks are already fully formed. The further loading results in a sharp increase in the contact spot diameter caused by cohesive spalling of the coating, which is weakened by the cracks. Fretting wear is described by characteristic dark regions arising near the edges of the contact spots (see Fig. 2b, c, shown by arrows 2), which are saturated with oxygen atoms to form oxide films and solid solutions of oxygen. These regions appear as early as after 10^4 loading cycles, and the area of the regions grows with the increase in the number of loading cycles up to 10^6. The fretting processes do not significantly influence the contact damage of the Ni-18.2Cr-3.3B-4.2Si coating subjected to additional heat treatment under the given loading conditions [10].

Figure 3 shows the dependences of the EC instrument readings on the number of loading cycles, which were measured on the contact spots after contact fatigue tests of the Ni-18.2Cr-3.3B-4.2Si coating subjected to additional heat treatment. It is obvious that for the Ni-18.2Cr-3.3B-4.2Si coating after high-temperature (1025 °C) annealing, at all the excitation frequencies of the EC transducer, the dependences of the EC readings on the number of loading cycles show a qualitatively similar behavior, i.e., the EC readings α decrease and increase with the increasing number of loading cycles, remaining on the average at the same level up to 5×10^5 cycles. At 8×10^5 loading cycles, the value α demonstrates an essentially more intensive decrease than at 5×10^4 and 3×10^5 cycles. The further increase in the value of α at 10^6 loading cycles does not compensate its intensive decrease observed at 8×10^5 cycles. As the excitation frequency f of the eddy-current device increases, the dependences, on the whole, become more pronounced; however, at the frequency f = 96 kHz (see Fig. 3c), the EC readings α vary less intensively than at the frequency f = 72 kHz (see Fig. 3b).

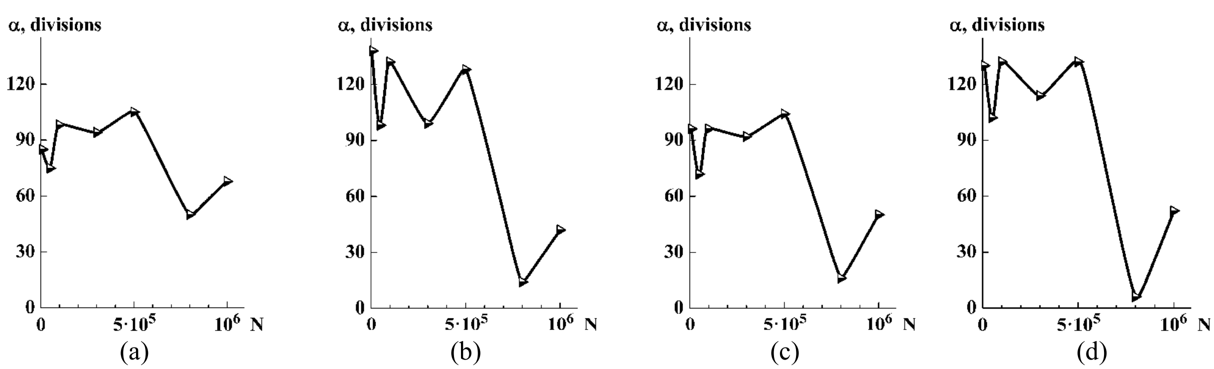


FIGURE 3. The influence of the number of loading cycles N on the EC readings α measured at frequencies of 36 kHz (a), 72 kHz (b), 96 kHz (c) and 120 kHz (d) within contact spots after contact fatigue tests of the Ni-18.2Cr-3.3B-4.2Si coating subjected to additional heat treatment

When measurements are made at different excitation frequencies f of the EC transducer, the differences in the dependences of the EC readings α on the number of loading cycles are determined by different electromagnetic field penetration depths δ [10] (as f increases, δ decreases). However, a more intensive change in the EC readings α at the frequency f = 72 kHz (see Fig. 3b) than that at the frequency f = 96 kHz (see Fig. 3c) may result from the progressing fatigue degradation in the lower layers. Consequently, after annealing, the Ni-18.2Cr-3.3B-4.2Si coating has the higher brittleness at contact fatigue loading. The complex behavior of the dependences of the EC readings on the number of loading cycles stems from the combined effects of cracking, cohesive spalling and compaction of the composite coating. Cracking decreases the EC readings due to the increasing resistivity of the surface layer containing cracks, while the latter increase the EC readings due to the decreasing resistivity of the coating. The formation of oxide films and solid solutions of oxygen on the coating surface does not significantly influence the electromagnetic measurement results [10].

CONCLUSIONS

The applicability of the eddy-current technique to testing the fatigue degradation of gas powder laser clad Ni-18.2Cr-3.3B-4.2Si coating, subjected to additional high-temperature annealing at 1025 °C, under contact loading has been established. It has been demonstrated that eddy-current testing of the fatigue degradation of the contact-loaded Ni-18.2Cr-3.3B-4.2Si coating after high-temperature annealing has certain limitations caused by the relatively high brittleness of this coating. This technique is applicable to testing only a sharp increase in the size of contact damages, which, under the used loading conditions, occurs at 8×10^5 cycles and results from the formation of a large number of peripheral ring cracks in the fracture zone and the corresponding decrease of the eddy-current readings α due to the increasing resistivity of the coating. The testing can be performed by measuring eddy-current readings at high excitation frequencies of the eddy-current transducer (f = 72-120 kHz), when the influence of the ferromagnetic steel base on the eddy-current readings α is minimum.

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